Climate Variability, Climate Change, and Sea-level Rise in Puget Sound: Possibilities for the Future

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Abstract
Since 1989 the Washington State Department of Ecology, Shorelands Program, has been studying the technical, policy, and practical implications of climate variability and climate change, especially sea level rise, for Washington's marine waters. In recent years Ecology's work has been carried out in concert with the University of Washington Climate Impacts Group, and the emphasis has shifted to include consideration of estuarine ecology issues.

During this decade we have learned much; and there yet remains much uncertainty. We know that the most likely scenario for future sea level rise is lower than a decade ago; but we also now know that the matter can be complicated by temporary sea level increases due to El Niño, thus complicating forecasts for coastal erosion or coastal flooding.

We suspect that there might be a climate nexus with the rapid spread of Cordgrass (*Spartina* sp.) since the 1980s, but the evidence is less than clear. There appears to be good evidence for a connection between the Pacific Decadal Oscillation and the Oyster Condition Index but we lack thorough, region-wide studies.

We know that most government agencies at all levels are reluctant to include a consideration of climate change in their land use and resource management planning, and that consideration short term climate variation such as El Niño fares little better.
This paper explores the certainties and uncertainties of climate variability and climate change for Washington's marine waters, and suggests areas of management concern and research needs.

Overview
This paper reviews historical sea-level rise, climate variation due to El Niño and La Niña[1]; and anthropogenic climate change as it applies to Puget Sound, and concludes with a review of current scientific and management questions.

Present Sea Level Rise
Past sea-level rise in Puget Sound is due to two principal universal causes, the relative importance of which varies throughout the world and within our region: global mean sea-level rise; and vertical land movements which produce a localized, relative sea level change. Both factors have affected Washington’s coast in the past, including the inland marine waters of Puget Sound.

Global mean sea-level rise has been in the range of 1 to 2.5 mm/yr during the past century (IPCC 1996). This has resulted from the warming, and therefore the thermal expansion of ocean waters; the melting of glaciers and ice fields; and other factors (Warrick and Oerlemans 1990).

Vertical land movements in western Washington result from a warping of the North American plate caused by a collision between the North American plate and the off-shore Juan de Fuca plate. Uplift occurs along the Washington coast, and subsidence within most of Puget Sound. Uplift ameliorates or negates sea-level rise; subsidence exacerbates sea-level rise. The rates of vertical land movement in Puget Sound and the Strait of Juan de Fuca range from +2.5 mm/yr at Neah Bay, to zero at Friday Harbor, to –1.4 mm/yr at

[1] Also collectively known as ENSO, the El Niño – Southern Oscillation.

Seattle, to -2.4 mm/yr at Tacoma (Holdahl and others 1989; Shipman 1989). Over a period of 100 years, 2 mm/yr amounts to 20 cm, or 0.66 feet.

As a result, sea-level rise in northern Puget Sound has been about equal to global change rates (1 to 2.5 mm/yr), while in southern Puget Sound sea-level rise has been up to double the global change rate, or up to 5 mm/yr. These regional variations in sea level change trends are illustrated in Figure 1. At Friday Harbor, where no vertical land movement occurs, the apparent sea level trend is +0.4 ft/century (+1.2 mm/yr), therefore the apparent local mean sea level increase. At Neah Bay, where uplift occurs, the apparent sea level trend is -0.4 ft/century (-1.2 mm/yr). At Seattle, where subsidence occurs, the apparent sea level trend is +1.0 ft/century (3 mm/yr).

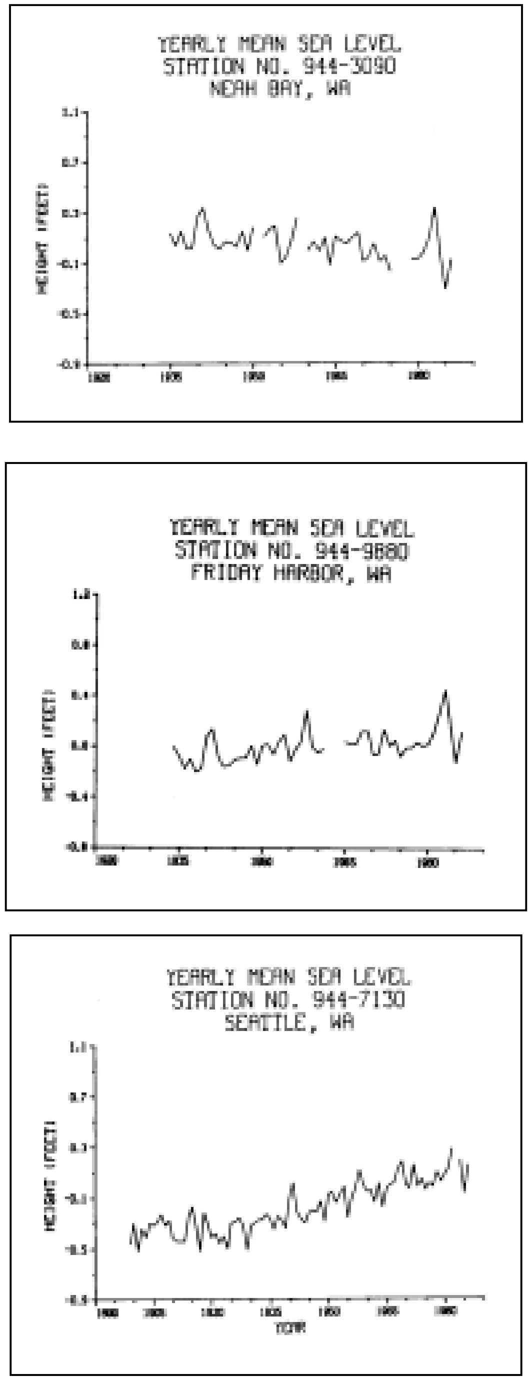

Figure 1. Yearly mean sea level trends at Neah Bay (1920 to 1990), Friday Harbor (1920 to 1990), and Seattle (1890 to 1990) tide gages (reproduced from Lyles and others 1988).

Present Climate Variability

Climate variability is a common fact of life in the Pacific Northwest. El Niño events have long been known to produce temporary sea level increases in the northeast Pacific Ocean, and to increase the frequency of extreme waves from the southwest, with resulting coastal erosion (Komar 1986). In Washington this effect has been most noticeable on the southwest Washington coast. The effect on sea level appears to be muted in Puget Sound, and of course, the ocean wave energy regimes do not propagate into Puget Sound.

During the 1982 to 1983 El Niño, for example, monthly mean water level at Newport, Oregon was up to 32 cm above monthly mean sea level, and up to 19 cm above the maximum monthly mean sea level (Komar 1992). During the 1997 to 1998 El Niño, monthly mean water level at Toke Point, Willapa Bay, Washington was up to 40 cm above monthly mean sea level (1980 to 1996), and up to 22 cm above the maximum monthly mean sea level (Kaminsky and others 1998). During the 1997 to 1998 El Niño, wave characteristics from the Grays Harbor wave gage indicated wave heights were nearly 1 m above normal during December and January, and 1.5 m above normal in February. Similarly, monthly mean wave periods were above normal by about 1 sec in February (Kaminsky and others 1998). Together, these factors would have increased wave energy, which is a function of wave height and wave period (Canning, in press).

Two large wave events occurred in January 1998. The first, during the night of 1-2 January, resulted in high water levels 10-15 cm above the predicted high tides for 2 January, and low water levels 33-40 cm above the predicted low tides. The combination of elevated seas and strong wind-induced waves resulted in shoreline erosion and wave runup into the primary dunes. An aerial reconnaissance on the afternoon of 2 January revealed shoreline retreat of up to 15 m at Point Brown, Ocean Shores, Washington; erosion of the primary dune; and widespread wave runup overwash into the primary dune field from Cape Shoalwater 50 km north to Copalis Head (Canning 1998; Canning, in press).

The second, and largest event of the season, occurred on 17 January (Kaminsky and others1998) when the Grays Harbor wave gage reported a significant wave height of 14.52 m and significant wave period of 22 seconds at 3:32 am (Pacific Standard Time) (predicted high tide at the nearby Point Brown tide gage was at 3:59 am). For the six hours prior to this event, significant wave heights were above 7 m with 20-second periods, and remained between 7.4 and 8.5 m for 5 hours following the event peak. An aerial reconnaissance on the afternoon of 17 January revealed clear evidence of high wave runup and overwash into the primary dunes throughout the Columbia River littoral cell, along with fresh sea cliff slumping, shoreline retreat, and extension of previous shoreline scarps. That both of these wave events occurred at high tide should not be overlooked; the on-shore effects of high-energy wave events that occur at low tide levels are substantially less (Canning, in press).

La Niña winters are associated with greater-than-normal winter rainfall (JISAO/SMA, in press), leading to bluff landsliding (Tubbs 1974). This is pattern is exemplified by the minor La Niña of 1996 to 1997 (Gerstel and others 1997), and the major La Niña of 1998 to 1999, both of which resulted in substantial damage to structures and infrastructure from landslides in urban areas, especially the Seattle metropolitan area.

Future Climate Change

Research conducted by the IPCC (Intergovernmental Panel on Climate Change) over the past 15 years now clearly indicates that the addition of greenhouse gasses[2] to the atmosphere by various industrial, land use, and agricultural practices has resulted in measurable changes to the atmosphere and resultant changes in Earth's climate (IPCC, 2001a, 2001b). In the PNW, climate models suggest that we can expect warmer, wetter winters, and warmer summers, with streamflow increasing in fall and winter, and decreasing in summer (JISAO/SMA, in press).

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[2] Carbon dioxide (CO_2) is the best know of the greenhouse gasses, which also includes methane, nitrous oxides, and CFCs. Indeed, any gas with more than 3 molecules functions as a greenhouse gas, but nitrogen (N_2) and oxygen (O_2), the primary constituents (~99%) of the atmosphere, are not.

Future sea-level rise due to anthropogenic climate change is expected to occur at a rate greatly exceeding that of the recent past, and is perhaps the best understood component of future climate change effects. Still, projecting future sea-level rise is a problematic enterprise, and different researchers arrive at varying conclusions based on different, yet valid, assumptions about atmospheric and oceanic interactions and future emission rates of greenhouse gasses. Currently, the range of "reasonable" scenarios varies from 3 cm to 124 cm sea-level rise by 2100, with "best estimate" values varying between 27 cm and 66 cm (Warrick and others 1996).

Scenarios for global sea-level rise in the next century developed by IPCC (Warrick and others 1996) are 2.0-8.6 mm/yr, compared to 1.0-2.5 mm/yr observed during the last century. On average (that is, IPCC's "best estimate"), global sea level is expected to be 50 cm higher by 2100 (with a range of 15 to 95 cm). The low sea-level rise scenario results from combining the lowest greenhouse gas emission scenario with the low climate and ice-melt sensitivities to greenhouse gas forcing. The high scenario results from combining the highest emission scenario with the high climate and ice-melt sensitivities.

However, regional differences in future sea-level rise will be caused by global variations in sea water temperature, atmospheric pressure, and ocean currents. The Canadian Center for Climate Modeling's CGCM1 model projects the following deviations from the global average by 2100: Eastern Pacific, +20 cm; Equatorial Atlantic, +5 cm; Northwest Atlantic –5 cm; Arctic Ocean, -35 cm (Hengeveld, 2000).

Therefore, a typical sea-level rise scenario , for a specific location in Puget Sound, based on IPCC's mid-range best estimate scenario, can be computed as shown in Table 1.

Table 1. Sea Level Rise Projections for Thurston County, Washington

SLR Component \ Year	1990	2000	2025	2050	2075	2100
Global Average SLR	0 *(0)*	2 *(0.1)*	10 *(0.3)*	20 *(0.7)*	35 *(1.2)*	50 *(1.6)*
East Pacific Surcharge	0 *(0)*	2 *(0.1)*	8 *(0.3)*	8 *(0.3)*	23 *(0.8)*	20 *(0.7)*
Local Subsidence	0 *(0)*	2 *(0.1)*	5 *(0.2)*	9 *(0.3)*	13 *(0.4)*	17 *(0.6)*
Total SLR	0 *(0)*	6 *(0.2)*	23 *(0.8)*	37 *(1.2)*	71 *(2.3)*	87 *(2.9)*

Table 1 Notes:

1. Sea-level rise values are in centimeters *(and feet)*. Totals for feet may appear not to add up properly due to rounding.
2. The subsidence range for Thurston County (1 to 2 mm/yr) was selected as 1.5 mm/yr.

Regionally, the geographical variance in the onset of climate change induced sea-level rise can be plotted as shown in Figure 2. The different rates of sea-level rise at the four tide gages result from the different rates of vertical land movement at those locations (see discussion on Present Sea Level Rise above). The present net negative sea level change at Neah Bay (see Figure 1) continues for a few decades before the rate of accelerated sea-level rise over comes the rate of uplift in that region of the state. The degree of sea-level rise projected at Tacoma for 2050 (~0.4 m), would not occur at Seattle until ~2060, at Friday Harbor until ~2080, and at Neah Bay until ~2100. Depending on the various climate sensitivity factors and response option assumptions, the sea-level rise scenarios could be 20% to nearly 200% of the mid-range scenario depicted.

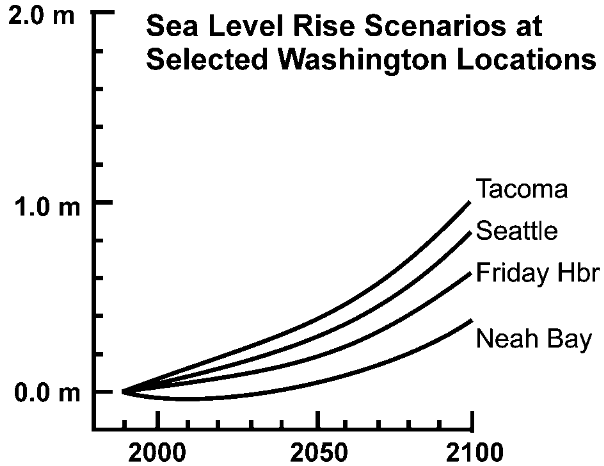

Figure 2. Future sea-level rise scenarios at Washington State tide gages Tacoma, Seattle, Friday Harbor, and Neah Bay.

Climate Change Effects

The first and second order effects on the coastal zone of climate change factors discussed above (Committee on Science, Engineering and Public Policy 1991; Committee on Engineering Implications of Changes in Relative Mean Sea Level 1987; Cline 1992; Canning 1991) can be summarized as follows:

- Long-term sea-level rise, and continued short-term increases due to El Niño, resulting in:
  - An increased frequency and magnitude of coastal erosion, shoreline retreat, and storm surge flood events, especially in conjunction with extreme storm events.
  - Changes in the tidal prism and salinity of embayments.
  - Coastal inundation of unprotected, low lying areas at locations such as Olympia’s central business district and “port peninsula”, or the shoreline from Mukilteo to Everett.
  - Coastal wetlands inundation, migration, and salinization.
  - Sea water intrusion?[3]
  - Coastal water table rise leading to:
    - Agricultural soils saturation.
    - Longer duration flooding.
    - On-site sewage disposal impeded.
    - Corrosion of underground pipes & tanks.

[3] Significant sea water intrusion into Washington’s coastal aquifers as a result of sea-level rise is considered problematic. Sea water intrusion presently occurs in many locations (e.g. San Juan, Island, and Thurston counties) due to high demands on coastal aquifers for domestic water supply. It is likely that the effects of ground water withdrawals for water supply will dwarf the effects of sea-level rise on sea water intrusion.

    - Solid & hazardous waste site leaching.
    - Storm drainage systems impeded.

- Increased winter rainfall, especially during La Niña events, will result in:
    - A greater frequency and magnitude of landsliding, especially in locales where topography and vegetation has been disturbed by land development and land use practices.
- The synergistic effects of sea-level rise and increased winter rainfall will result in:
    - An increased frequency and duration of river-mouth flooding, especially when river flood flows arrive at the coast coincident with high tide.

Response

Reaction to climate change induced sea-level rise response typically seems to be more problematic than is warranted. There are a number of response programs in effect that address as much, or nearly as much, uncertainty as exists with respect to sea-level rise. Response to climate change induced sea-level rise might best be though of in terms of risk management.

One useful analogy is the way we deal with response to stormwater routing and flood management. Much of this response is based on the so-called 100-year storm[4], despite the fact we lack 100 years of weather records for many locations. In addition, we have long known that storm flows in a particular basin, resulting from a particular storm intensity, chronically increase over time as forest cover decreases and impervious surface coverage increases (Dunne and Leopold 1978). And yet we are able to ignore these issues and confidently base public policy and engineering design on the concept of the 100-year storm.

We do this by assigning *de facto* risk levels to particular land uses or infrastructure by associating them with storm or flow events. When relatively little is at risk in the way of infrastructure investment or public inconvenience or risk, we might, for example, design a secondary county road or street bridge or culvert to accommodate the flow from a 25-year event. When more is at risk we choose the 100-year event or even the 500-year event as the criteria.

There appears to be no reason why we cannot take a similar approach to sea-level rise response.

When relatively little is at stake in the way of infrastructure investment or public inconvenience or risk, we could choose to design for a conservative or "low end" sea-level rise scenario. When more is a stake we could choose to design for a mid-range scenario or even a more "aggressive" sea-level rise scenario.

Questions for the Future

At the Climate Impacts Group (University of Washington) we are shifting our research emphasis in the Coastal Sector from one of coastal hazards (e.g. sea-level rise induced erosion, and rainfall induced landsliding) to one of asking questions about integrated watershed–estuary ecology. Some of the questions we are asking are: What are the synergistic effects of sea-level rise and runoff changes on estuarine salinity? In what ways might water quality changes effect estuarine productivity and biodivirsity? What effect might warming water temperatures have on exotic species recruitment? How might these effects cumulatively affect the shellfish industry or the harvest of wild stocks of fish or crustaceans? Do we have adequate institutional response capabilities?

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[4] The so-called 100-year event is really an event which has 1% chance of occurrence each year. Similarly, a 25 year event has a 4% probability of occurrence each year, and a 500 year event a 0.2% probability.

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